Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **23**, 685–703 (1998)

MINERAL MAGNETIC CHARACTERIZATION OF SEDIMENT SOURCES FROM AN ANALYSIS OF LAKE AND FLOODPLAIN SEDIMENTS IN THE CATCHMENTS OF THE OLD MILL RESERVOIR AND SLAPTON LEY, SOUTH DEVON, UK

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Received 7 April 1997; Revised 6 October 1997; Accepted 4 November 1997

ABSTRACT

Research on suspended sediment transport in the catchments of the Old Mill reservoir and Slapton Lower Ley, South Devon, has attempted to discriminate changing catchment sources on the basis of downcore variations in the mineral magnetic properties of lake, reservoir and floodplain sediments. Here, we examine these downcore variations and also explore the variability in catchment sources and the influence of topographic controls on mineral magnetic signatures of topsoils and subsoils. Particle size controls on the mineral magnetic signatures are explored by an analysis of a fractionated sediment sample, whilst the possible impact of diagenesis is assessed by an examination of the Mn profiles in the lake and reservoir sediments. From this analysis it is evident that the mineral magnetic signatures of well sorted floodplain deposits are more likely to reflect the particle size composition of the transported material. By contrast, the mineral magnetic record in the sediment of Slapton Ley appears to be most strongly influenced by dissolution of magnetic minerals. The sediment of the Old Mill reservoir provides the only suitable record for the application of a simple mixing model which is developed in order to quantify changes in the relative contribution of topsoil and subsoil through time. The research has important implications for attempting to reconstruct sediment sources in highly eutrophic lakes and emphasizes the uncertainty in the application of simple mixing models. © 1998 by John Wiley & Sons, Ltd.

KEY WORDS: environmental magnetism; sediment source tracing; particle size; diagenesis; mixing models

INTRODUCTION

Since the pioneering work of Oldfield *et al*. (1979) and Walling *et al*. (1979), numerous studies have used the mineral magnetic signatures of potential source materials in order to identify the provenance of suspended sediment or recently deposited floodplain, lake and reservoir sediments. Controls on the mineral magnetic signatures recorded in these transported and deposited sediments include the primary magnetic mineralogy (Shankar *et al*., 1994), magnetic grain size (Dearing *et al*., 1985, 1996), the particle size of the transported sediment (Björck *et al*., 1982; Bradshaw and Thompson, 1985) and diagenetic changes in source materials (Singer *et al*., 1996) and deposited sediments (Hilton and Lishman, 1985; Hilton *et al*., 1986; Anderson and Rippey, 1988; Snowball and Thompson, 1988; Farina *et al*., 1990; Fassbinder *et al*., 1990; Mann *et al*., 1990), in addition to a range of effects attributed to anthropogenic inputs (cf. Thompson and Oldfield, 1986). The appropriateness of an exclusively detrital model of the magnetic mineral origins in lake sediments is clearly thrown into doubt by many of the studies identified above. In hyper-eutrophic lakes, for example, magnetite solution may take place within strongly reduced organic sediments (Anderson and Rippey, 1988), whilst the formation of authigenic ferrimagnetic iron sulphides, such as greigite, appears to occur in freshwater muds in contact with sulphur-rich marine sediments (Snowball and Thompson, 1988). There may also be situations in which the magnetic properties of lake sediment cores include contributions from bacterial magnetite (Kirschvink *et al*., 1985; Lovely *et al*., 1987). Further detailed discussion of these issues and their relevance to

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CCC 0197-9337/98/080685–19 $17.50

the interpretation of the mineral magnetic signatures of lake sediment cores is given by Hilton (1987) and Oldfield (1991).

Attempts to model sediment source linkages on the basis of their mineral magnetic signatures usually simplify the problem by analysing the bulk source materials (Shankar *et al.*, 1994), by functionally separating source materials into particle size bands which approximately replicate those of the deposited materials (Yu and Oldfield, 1989) or by analysing fractions which are thought to be representative of different hydraulic transport components (Caitcheon, 1993). A variety of approaches have also been used to model the magnetic signatures. These include simple models based on single magnetic parameters, such as frequency-dependent susceptibility (Dearing and Foster, 1986), and multivariate methods, using measured and derived magnetic parameters, such as principal component analysis, multiple regression and linear programming techniques and the solution of simultaneous equations (Thompson, 1986; Yu and Oldfield, 1989; Caitcheon, 1993; Lees, 1994; Shankar *et al.*, 1994).

Over the last decade, several research projects have been conducted by the authors in the catchments of the Old Mill reservoir and Slapton Ley, South Devon. These studies have focused on historical sediment yield reconstruction and the analysis of sediment budgets in the two catchments (cf. Owens, 1990; Foster *et al.*, 1993, 1996; Foster and Walling, 1994; Owens *et al.*, 1997). This paper provides a detailed interpretation of downcore variations in the mineral magnetic signatures of lake and floodplain sediment cores by considering new data which examine the variability in soil characteristics, an analysis of the particle size controls on the mineral magnetic signature, and the presentation of new geochemical data for the lake sediments. We focus first on downcore variations in mineral magnetic properties of lake, reservoir and floodplain sediments, secondly on the spatial variability and topographic controls on the magnetic signatures of catchment topsoils, thirdly on the potential for discriminating topsoils and subsoils, fourthly on the particle size and possible diagenetic controls on the mineral magnetic signature of deposited sediments, and, finally, on the development of a mixing model to discriminate catchment sediment sources (topsoil and subsoil), using the lake sediment record from the Old Mill reservoir, by solving simultaneous equations.

SITE DESCRIPTION

Slapton Ley, a natural lake, and the Old Mill reservoir are located in the South Hams region of South Devon (Figure 1). Both catchments are underlain by slates, shales, siltstones and mudstones of Devonian age. Soils of the Denbigh series, which are stony, well drained and of moderate depth, are to be found throughout the area. Manod series soils, which are free-draining fine loamy soils, occupy the main valleys of the contributing catchments. Mean annual preciptiation for Slapton (1961–1993) is 1049 mm. Precipitation is highly variable, with monthly coefficients of variation exceeding 40 per cent (Ratsey, 1975). The freshwater lagoon of Slapton Ley developed as a result of the shoreward movement of sediment as post-glacial sea levels rose (Hails, 1975) and radiocarbon dates on peats underlying the lake sediments give the approximate age of the closure of the lagoon as 2889 ± 50 years BP (1 standard deviation) (Morey, 1976). The Old Mill reservoir was constructed between 1938 and 1942 to provide a reliable water supply for the nearby town of Dartmouth. The dam was constructed across a narrow steep-sided valley and comprises an earth-cored structure of some 80 m in length with a spillweir in the southeast corner.

Two main catchments drain directly into Slapton Lower Ley, of which the largest is the Start (Figure 1). An important contrast between the Start valley and the catchment of the Old Mill reservoir lies in the presence of a broad, rapidly sedimenting floodplain in the former location (cf. Owens, 1990) which is not evident in the Old Mill catchment. The Start floodplain has been estimated to trap *c*. 38 per cent of the sediment eroded from hillslopes in the Start catchment. Soil erosion rates in the Start catchment are estimated to be *c*. 80 t km^{-2} a^{-1}, and the floodplain therefore traps an equivalent of *c*. 30 t km^{-2} a^{-1}, with a further 26 per cent (*c*. 21 t km^{-2} a^{-1}) accumulating behind lateral hedge boundaries (Owens *et al.*, 1997). As a consequence, sediment yields to Slapton Lower Ley are estimated to be only *c*. 29 t km^{-2} a^{-1}. Transfer of sediment from the Upper Ley to the Lower Ley is estimated to be *c*. 118 t annually (Foster *et al.*, 1996). In contrast to the sediment yields from the Start catchment, Foster and Walling (1994) estimated suspended sediment yields to the Old Mill

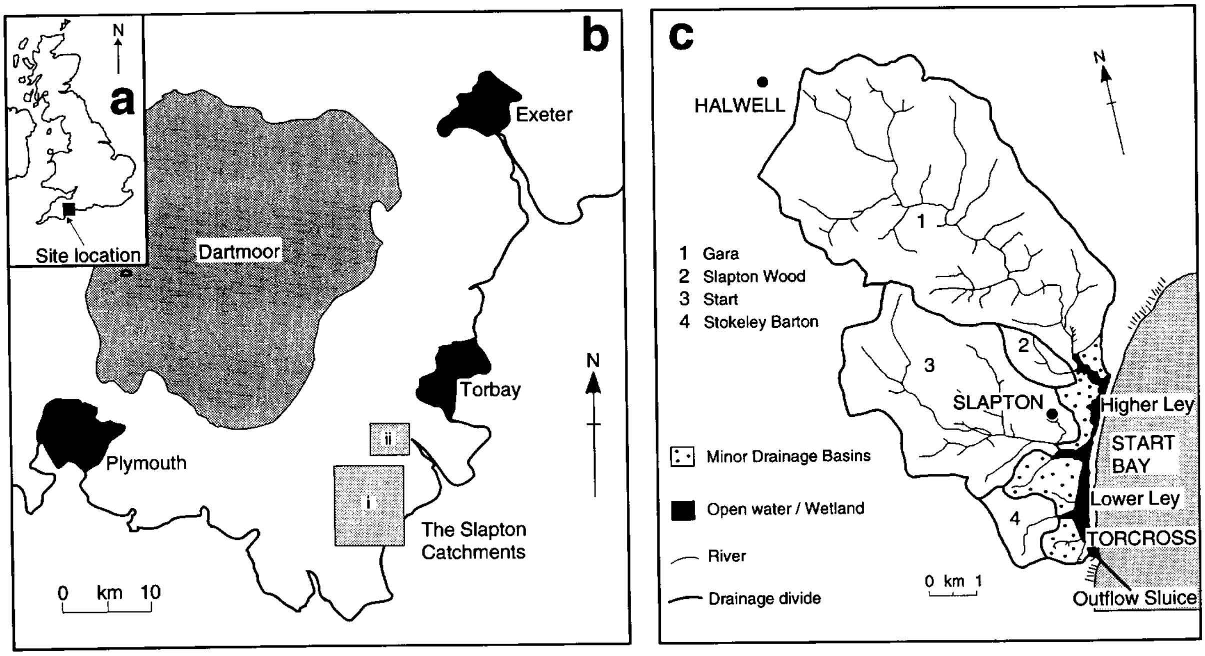

Figure 1. Location of research sites (a and b) i the Slapton Catchments; ii Old Mill Reservoir with details of the catchments of Slapton Ley (c)

reservoir for the period 1954–1992 to be *c*. 63 t km^{-2} a^{-1} and, over the last 15 years, to be *c*. 90 t km^{-2} a^{-1}. These results emphasize the differences between the sediment budgets of the two catchments and the differences in the amount of sediment delivered to Slapton Lower Ley and the Old Mill reservoir.

Details of the two study catchments are summarized in Table I. Further details are given in Foster and Walling (1994) and Foster *et al*. (1996), and detailed descriptions of Slapton Ley are given by O'Sullivan (1994).

MATERIALS AND METHODS

Sediment and soil sampling and laboratory preparation

Sediment cores were retrieved from Slapton Ley and the Old Mill reservoir using a Mackereth-type corer (Mackereth, 1969) (Figure 2). A floodplain core was collected from the lower Start valley using a percussion corer. These cores were extruded into petri dishes at 2·0, 1·0 and 1·0 cm intervals respectively. Samples were oven-dried at 40°C overnight and subdivided for analysis of loss on ignition, particle size and mineral magnetic properties.

Forty-five surface (0–5 cm) soil samples were collected by auger along three transects across the Old Mill catchment (Figure 2) in addition to seven subsoil samples collected from hillslope locations at >40 cm depth. These samples were oven-dried at 40°C overnight, dry-sieved through a 4ϕ (63 μm) mesh and analysed for loss on ignition, particle size and mineral magnetic properties.

Table I. Characteristics of the Old Mill and Slapton Lower Ley catchments

	Old Mill	Slapton Lower Ley
Catchment area (ha)	159·53	1232*
Lake area (ha)	1·85	77·1
Catchment: lake area ratio	86:1	16:1
Maximum altitude (m)	194	183
Minimum altitude (m)	144	*ca* 3
Relative relief (m)	53	178

* Start and Stokeley Barton catchments only (Figure 1)

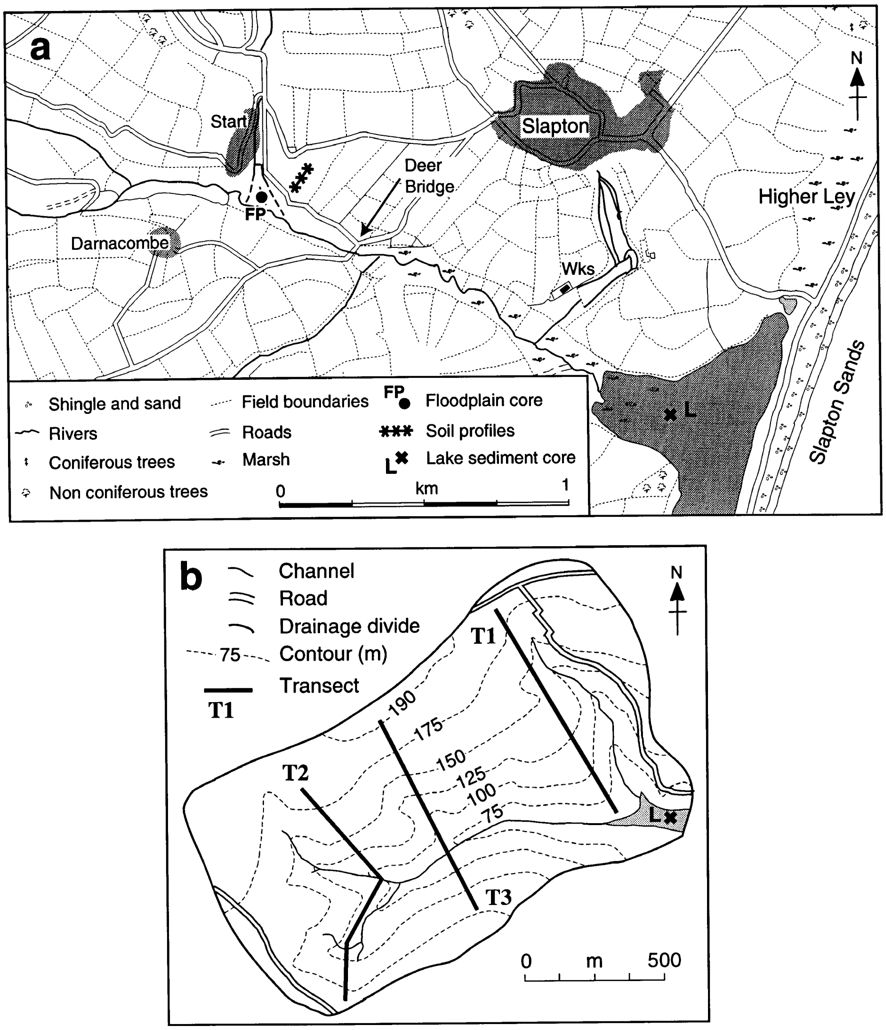

Figure 2. Lake, reservoir, floodplain and soil sampling locations in the catchments of Slapton Lower Ley (a) and the Old Mill reservoir (b)

Soil cores were retrieved from three locations in the Start catchment (Figure 2). Samples were collected by auger and subdivided into 5 or 10 cm increments. The samples were oven-dried at 40°C overnight, dry-sieved through a –1ϕ (2000 µm) mesh and analysed for particle size and mineral magnetic properties.

A bulk sediment sample (*c.* 3 kg) was recovered from the floodplain of the Start valley. This sample was initially dried overnight at 40°C, physically dispersed in a ball mill for 20 min and dry-screened through a –1ϕ mesh sieve. The sample was resuspended in deionized water (10 g in 50 ml) and organic matter was removed by adding 5 ml of 100 vol. H_2O_2. The solution was left overnight in a fume cupboard. It was subsequently wet-sieved at 1ϕ intervals to 4·0ϕ. Below 4ϕ, 8 g subsamples were dispersed in 500 ml deionized water with 5 ml dispersant (50 g sodium hexametaphosphate and 7 g anhydrous Na_2CO_3, dissolved in 1 litre deionized water) (Avery and Bascombe, 1982). Suspensions were allowed to settle in a sedimentation column in the laboratory for periods ranging from 3 min to 18 h in order to extract particle size fractions at 1ϕ intervals between 4 and 9ϕ in addition to the sub-9ϕ fraction. Settling times were calculated according to the method of Gibbs *et al.* (1971). The suspension was siphoned from the sedimentation column at 20 cm depth and transferred to a 5 litre polypropylene bottle. (For each particle size fraction, sedimentation was repeated four times.) Suspensions were flocculated by adding 20 ml 1 mol. $Al_2(SO_4)_3$. $18H_2O$ solution, the liquid decanted, and the remaining suspension centrifuged, washed with deionized water three times, and oven-dried at 40°C. A control sample,

Table II. Measured and derived magnetic measurements

Susceptibility	Measured (M)/ Derived (D)	Instrument	Units
χ_{lf}	M	Bartington MS2B	$10^{-6} m^3 kg^{-1}$
χ_{hf}	M	Susceptibility meter	$10^{-6} m^3 kg^{-1}$
χ_{fd}	D		$10^{-9} m^3 kg^{-1}$
$\chi_{fd\%}$	D		%
$ARM_{(40\mu T)}$	M	Molspin variac	$mAm^2 kg^{-1}$
$IRM_{(0\cdot025–0\cdot8T)}$	M	Pulse magnetizer	$mAm^2 kg^{-1}$
$IRM_{(-0\cdot1T)}$	M	Molspin fluxgate Magnetometer	$mAm^2 kg^{-1}$
S ratio	D	$(IRM_{(-0\cdot1T)}/IRM_{(0\cdot8T)})$x–1	dimensionless
HIRM	D	$(IRM_{(0\cdot8T)} \times (1–S\ ratio))/2$	$mAm^2 kg^{-1}$
HIRM:χ_{fd}	D		μAm^{-1}

with no particle size fractionation, was measured for all magnetic properties prior to the above treatments and remeasured after treatment.

Laboratory measurements

The screened soil, floodplain, and lake and reservoir sediment samples were measured for loss on ignition at 450 and 850°C for 12 h and 2 h in order to estimate organic matter and carbonate content respectively. The particle size distribution of the sub-0 and –4ϕ fractions were analysed using a Malvern Instruments laser granulometer. Diatom silica was estimated from an analysis of the alkali-soluble component in lake sediments. Pretreatment of dry sediment with hydrogen peroxide and concentrated hydrocholoric acid was followed by digestion in a 10 per cent sodium carbonate solution (cf. Foster *et al*., 1985). Eight catchment soil samples were analysed by the same method for comparative purposes.

All magnetic measurements were made on 10 ml soil and sediment samples. Low and high frequency susceptibility were measured using a Bartington MS2B dual frequency sensor. Anhysteretic remanence (ARM) was measured on a Molspin fluxgate magnetometer after an (ARM) was imparted by smoothly ramping down a mains frequency alternating field of 0·1 T while the samples were subjected to a steady field of 40μT. Other remanence measurements were also made on a Molspin fluxgate magnetometer after subjecting samples to a forward magnetic field of 0·8 T and a reverse field of 0·1 T in a Molspin pulse magnetizer. These measurements allowed the derivation of IRM (0·8 T and –0·1 T), the S ratio and HIRM values (see Table II). Selected samples were subjected to a steadily increasing magnetic field at intervals between 0·025 and 0·8 T. IRM was measured immediately after magnetization and the remanence at each field was expressed as a percentage of saturation (assumed to be reached at a forward field of 0·8 T) in order to produce IRM acquisition curves. Measured and derived magnetic parameters, with their associated units, are given in Table II.

RESULTS

Lake, reservoir and floodplain cores

Downcore profiles for selected mineral magnetic properties of sediment cores taken from the Old Mill reservoir, Slapton Lower Ley and the Start valley floodplain are shown in Figures 3 and 4. Summary statistics are given in Table III. The floodplain and Old Mill reservoir cores were dated using Cs-137 (Foster and Walling, 1994; Foster *et al*., 1996). The Slapton Ley core was dated by physical and geochemical cross-correlation with a Pb-210 dated core published by Heathwaite and Burt (1993) (cf. Foster *et al*., 1996).

From Figure 3, it is evident that the Slapton Ley core exhibits an increase in χ_{lf}, χ_{fd} and HIRM towards the mud–water interface over the 56 years of sedimentation represented by the core. The HIRM:χ_{fd} ratio ranges from almost 0·025 to *c*. 0·3 and $\chi_{fd\%}$ values average around 5 per cent. χ_{lf} and χ_{fd} values are considerably higher in the sediments of the Old Mill reservoir than in Slapton Ley, whilst HIRM values are only slightly higher and $\chi_{fd\%}$ values approach 9 per cent. The existence of significantly lower χ_{fd} values in Slapton Ley has a consequent impact upon the HIRM: χ_{fd} ratio. ARM values for the sediment of Slapton Ley and the Old Mill reservoir are

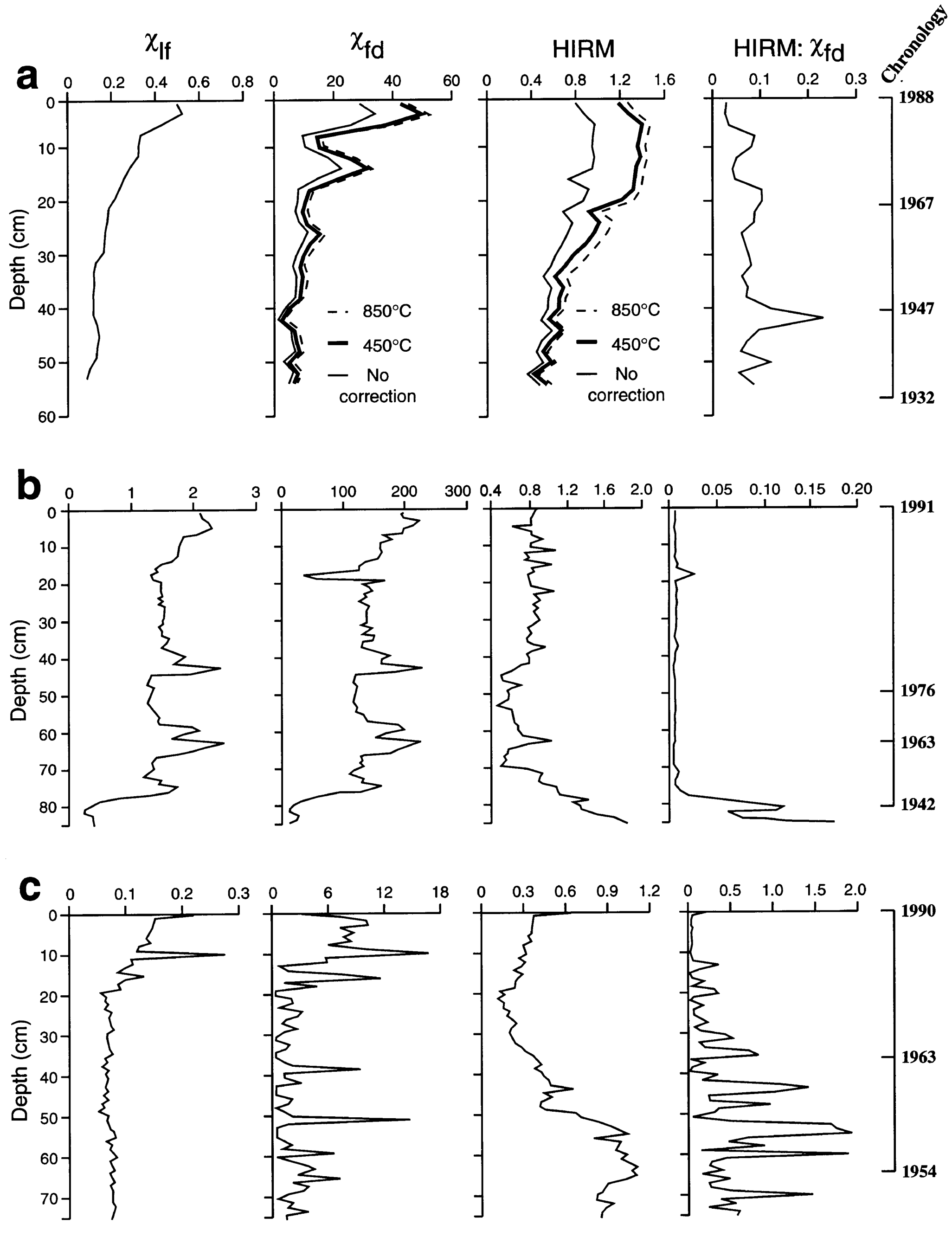

Figure 3. Selected mineral magnetic signatures for the sediments of Slapton Lower Ley (a), the Old Mill reservoir (b) and the Start valley floodplain (c) (see Figure 2 for sampling locations)

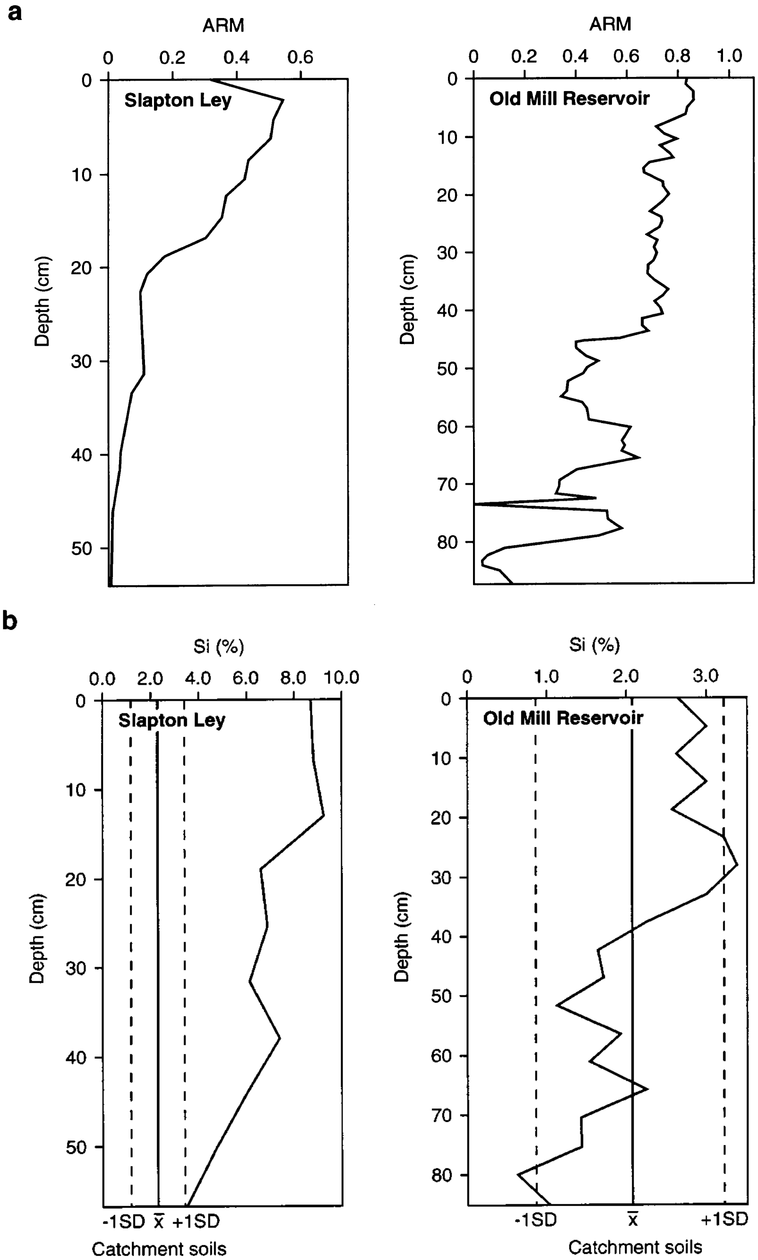

Figure 4. ARM (a) and silica content (b) of the Slapton Ley and Old Mill reservoir cores (mean, solid vertical line, and standard deviation, broken vertical line, of eight catchment soil samples for silica are plotted for comparison)

plotted in Figure 4. ARM decreases markedly with depth in the Slapton core and less markedly in the sediments of the Old Mill reservoir. All susceptibility and remanence measures are considerably lower in the core from the Start valley floodplain than in the cores from Slapton Ley or the Old Mill Reservoir. The HIRM:χ_{fd} ratio, however, approaches 2 in the floodplain core, whilst $\chi_{fd\%}$ values average 3·2 per cent.

Diatom silica concentrations in the Old Mill reservoir (Figure 4) are indistinguishable from the background amorphous silica concentrations in catchment soils. By contrast, diatom silica concentrations in the Slapton Ley sediments approach 9 per cent in the upper 20 cm of the core, some 7 per cent higher than catchment soils.

Table III. Summary statistics for soils and sediment samples (corrected for loss on ignition) collected in the Old Mill and Start catchments

	Slapton Ley (n=35)		Old Mill reservoir (n=85)		Start floodplain (n=74)		Arable* topsoils (n=20)		Grassland* topsoils (n=16)		Woodland* topsoils (n=9)		Subsoils (n=7)	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
χ_{lf}	0·290	0·191	1·726	0·466	0·093	0·037	4·97	3·66	3·66	2·63	4·58	4·18	0·55	0·35
χ_{fd}	14·97	12·15	154·80	49·13	3·94	3·44	458·61	192·58	366·34	289·12	459·85	439·58	61·1	21·43
$\chi_{fd\%}$	5·28	2·89	8·73	1·45	3·20	3·80	9·22	0·81	9·38	1·78	9·22	1·15	7·03	2·43
ARM	0·186	0·180	0·576	0·214	—	—	1·641	0·583	1·254	0·702	0·740	0·622	1·180	1·156
$IRM_{(0·8T)}$	6·17	3·79	12·85	3·07	1·63	1·203	32·99	13·46	24·35	14·33	19·37	14·13	7·69	3·29
$IRM_{(-0·1T)}$	−4·31	2·00	−10·92	3·20	−0·403	1·373	−29·76	12·43	−21·53	13·28	−17·55	13·46	−3·09	4·14
S ratio	0·691	0·104	0·823	0·145	0·056	0·52	0·897	0·024	0·827	0·133	0·866	0·069	0·225	0·533
HIRM	0·909	0·330	0·965	0·259	0·611	0·313	1·43	0·56	1·18	0·54	0·70	0·30	2·30	0·624
HIRM: χ_{fd}	0·105	0·051	0·013	0·027	0·386	0·466	0·004	0·002	0·009	0·009	0·005	0·004	0·046	0·033

* Samples collected from the Old Mill catchment only

However, the difference between the average magnetic susceptibility and remanence values for lake sediments and catchment soils reported in Table III cannot be accounted for in terms of dilution by diatom silica and/or organic matter concentrations.

The sediments of Slapton Ley have organic matter contents ranging from *c*. 14 per cent at the base to *c*. 30 per cent in the upper 25 cm. The impact of organic matter on χ_{fd} and HIRM values is shown on Figure 3a (organic matter correction is only required for the concentration parameters χ_{lf}, χ_{fd}, $IRM_{(0·8T,\,-0·1T)}$ and HIRM). The corrected values accentuate the upcore increase in both χ_{fd} and HIRM. By contrast, organic matter concentrations in the Old Mill sediments change little throughout the core (mean 14·49 per cent, st. dev. 1·39 per cent). The organic matter content of the floodplain core has a mean of 15·68 per cent with a standard deviation of 6·87 per cent. Whilst highly variable, there are no discernible trends in organic matter content in the core. Low organic matter contents are associated with well-sorted coarse sediments which are indicative of high energy overbank flows. The summary of magnetic properties given for lake, reservoir and floodplain sediments in Table III is corrected for organic matter content to enable direct comparison with the soils data.

Whilst it would be tempting to ascribe the higher organic matter and diatom silica content of the Slapton Ley core to a higher productivity in the Ley than in the Old Mill reservoir, it is evident from the chronologies of Figure 3 that the sedimentation rate in the Old Mill reservior is almost double that of Slapton Ley. In consequence, the significantly higher organic matter and diatom silica contents of the Slapton Ley core could simply reflect less dilution by allochthonous sediment influx.

Surface soils in the Old Mill catchment

Summary statistics for the organic matter corrected mineral magnetic signatures of the arable, grassland and woodland topsoils collected from the Old Mill catchment are given in Table III and selected boxplots comparing the distribution of χ_{fd}, $IRM_{(0·8T)}$, HIRM and the HIRM:χ_{fd} ratio are given in Figure 5. These summary statistics show high measured susceptibility and remanence values in comparison with lake and floodplain sediments. Average $\chi_{fd\%}$ values exceed 9 per cent from all potential topsoil sources and the HIRM: χ_{fd} ratio is consistently low in all samples. The boxplots show considerable overlap between possible topsoil sources in this catchment. The statistically significant differences between these contributing sources were identified using paired Student *t*-tests, the results of which are summarized in Table IV. Whilst statistically significant differences can be identified between many of the mineral magnetic properties of grassland and arable topsoils, the large scatter and poor discrimination between these sources suggest that attempts to quantitatively reconstruct topsoil sources, based on an analysis of the Old Mill reservoir sediments, would be unreliable.

Figure 6 plots the distribution of mineral magnetic signatures in relation to topography and soil depth along Transect 1 of the Old Mill catchment (Figure 2b). The transect includes both pasture and recently ploughed soils. The slope profile has a topographic hollow some 300 m from the drainage divide where the soil depth exceeds 1 m. The concave slope segments at *c*. 200 and 400–800 m from the drainage divide have thin soil

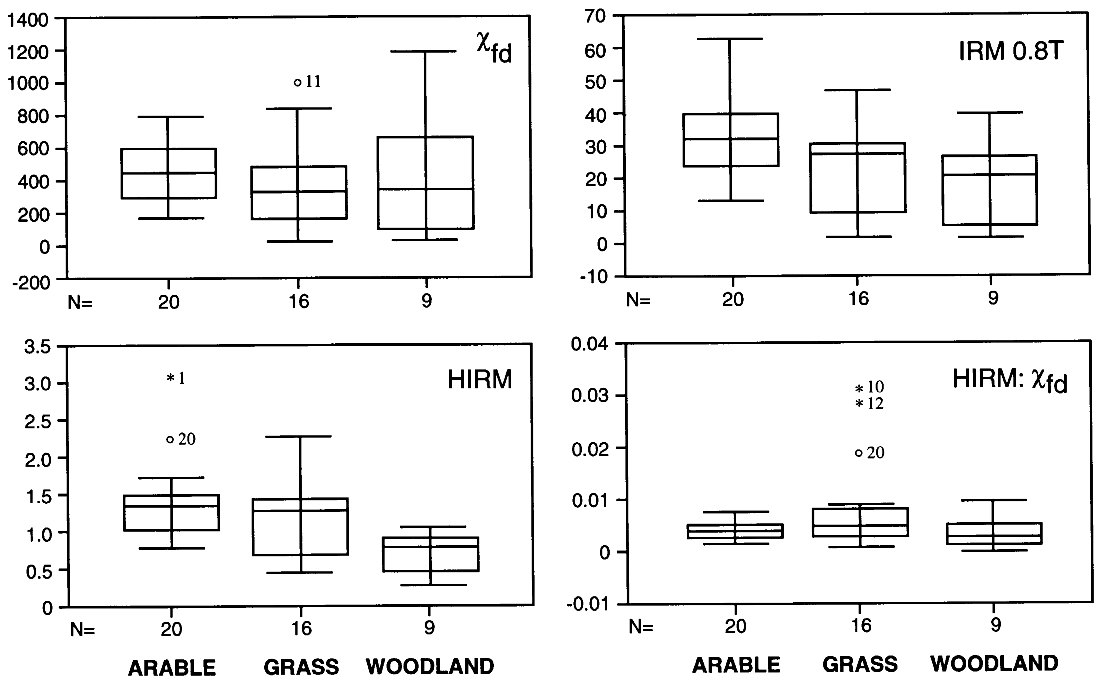

Figure 5. Boxplots comparing selected mineral magnetic signatures for the sub-63 µm fraction of arable, grassland and woodland topsoils (0–5 cm) in the Old Mill catchment. The boxes contain 50 per cent of the values between the 75th and 25th percentiles of the frequency distribution, whilst the whiskers extend to the maximum and minimum values excluding outliers and extremes. An outlier (o) is defined as a value more than 1·5 box lengths away from the box and an extreme value (*) as more than 3 box lengths away from the box. The numbers associated with outliers and extreme values are the sample numbers. The line across the box indicates the median value of the data set

covers. These thinner soils are characterized by a lower χ_{lf}, χ_{fd} and $IRM_{(0{\cdot}8T)}$ and a higher HIRM and HIRM:χ_{fd} ratio, although $\chi_{fd\%}$ values remain relatively constant irrespective of slope position and soil depth. These shallow topsoils appear to be characterized by the magnetic signatures of subsoils which are within reach of the plough when cultivated (see below). At the slope foot adjacent to the stream channel, most magnetic values decline significantly, but this pattern is especially marked for χ_{lf}, χ_{fd}, $IRM_{(0{\cdot}8T,-0{\cdot}1T)}$ and HIRM.

Whilst a number of measured and derived parameters are obtained from measurements of dual frequency susceptibility and remanence, in reality these parameters replicate either remanence or susceptibility signatures by physical definition or by calculation. This is well illustrated in Figure 7 and Table V where seven mineral magnetic parameters for the 45 topsoils are included in a principal component analysis (PCA). The PCA produced two significant components with eigenvalues above 1·0 which, in combination, explained some 92 per cent of the variance in the total data set. Remanence properties load highly on component 1 and susceptibility properties on component 2. This analysis suggests that the use of multiple magnetic signatures for

Table IV. Significant mineral magnetic differences (t-test; 0·05 probability) between topsoils of the Old Mill catchment under grassland, woodland and arable cultivation (all corrected for loss on ignition)

	Woodland and arable	Woodland and grassland	Arable and grassland	Notes
χ_{lf}	NS	NS	0·05	Arable higher
ARM	0·05	NS	0·05	Arable highest
$IRM_{(0{\cdot}8T)}$	NS	NS	0·05	Arable higher
$IRM_{(-0{\cdot}1T)}$	NS	NS	0·05	Arable higher
S ratio	NS	NS	0·05	Arable higher
HIRM	0·05	NS	NS	Arable higher
HIRM:χ_{fd}	NS	NS	0·05	Grassland higher

Woodland, n = 9; arable, n = 20; grassland, n = 16. NS = Not significant at 0·05 probability

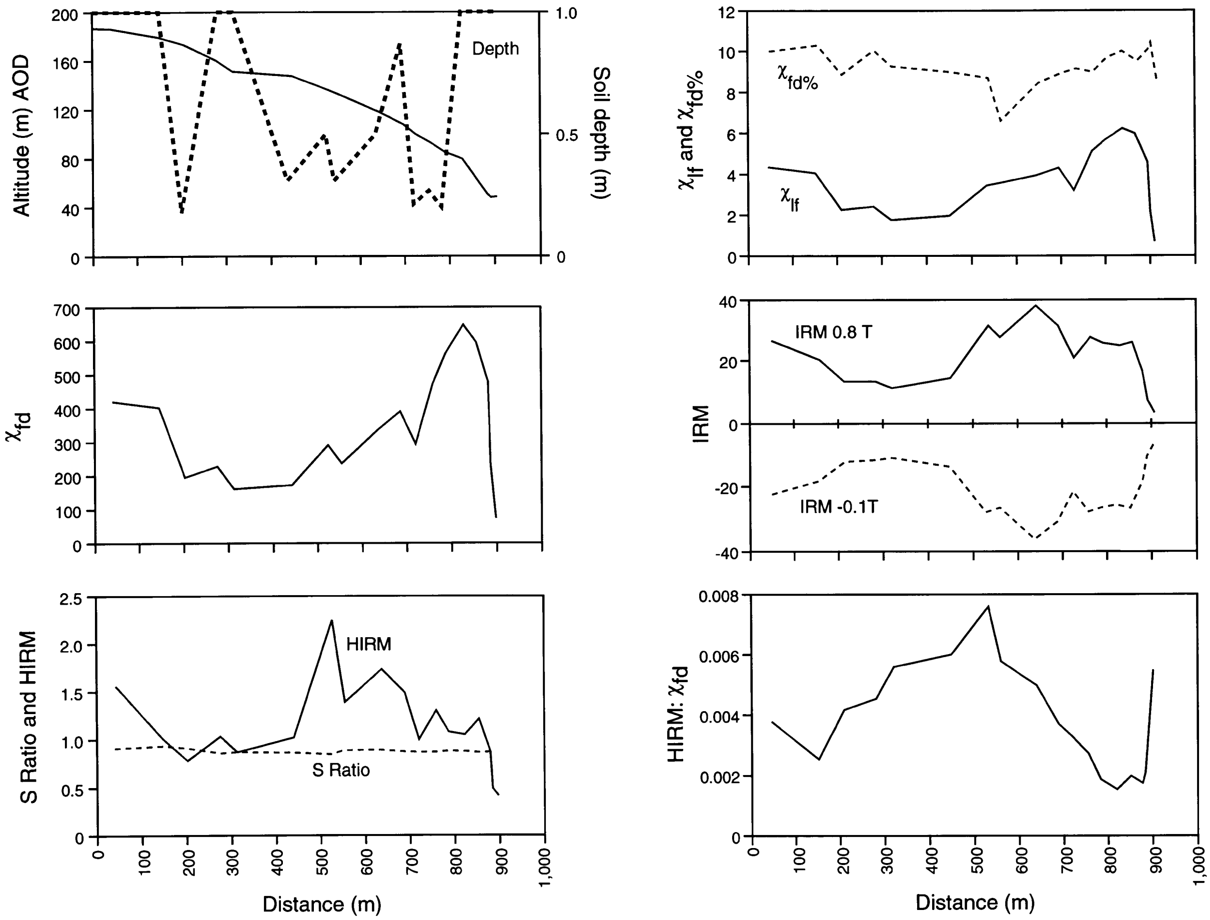

Figure 6. Topography, soil depth and mineral magnetic signatures along Transect 1 of the Old Mill catchment (see Figure 2 for sampling locations)

sediment source modelling using multiple regression or other statistical techniques could be invalidated by high intercorrelation amongst the independent variables and that at best only two statistically independent parameters could be used. Similar results for a range of natural and environmental materials have been reported by Lees (1994) and the mixing model subsequently developed in this research project therefore used only one 'magnetite' and one 'hematite' signature (χ_{fd} and HIRM; see below).

Soil profile and subsoil characteristics of the Old Mill and Start catchments

Figure 8a plots χ_{fd} and $\chi_{fd\%}$ profiles for a transect of three soil cores collected upslope of a lateral hedge boundary from a pasture field in the Start catchment (see Figure 2a for sample locations). For mid and head of slope profiles, χ_{fd} values lie between 150 and 200 to depths of around 30 cm within the profile. Below this depth, χ_{fd} declines rapidly, whilst $\chi_{fd\%}$ falls more slowly in these well drained subsoils. The slope foot profile is complex. The upper part of the profile is similar to that of the upslope cores. However, below *c.* 25 cm, χ_{fd} values increase to over 200 at a depth of 40 cm and subsequently decrease to below 20 at a depth of *c.* 52 cm. This complex profile may represent periods of soil accumulation as a result of erosion from upslope areas. The characteristic topsoil signatures at depths of between 28 and 52 cm may have been produced as a result of surface wash processes moving sediment downslope. The characteristic subsoil signatures at between 18 and 28 cm depth may be the result of rill and/or gully erosion processes moving subsoils downslope. The presence of Cs-137 at a depth of *c.* 24 cm in this profile suggests that the depositional sequence above this depth developed since 1954.

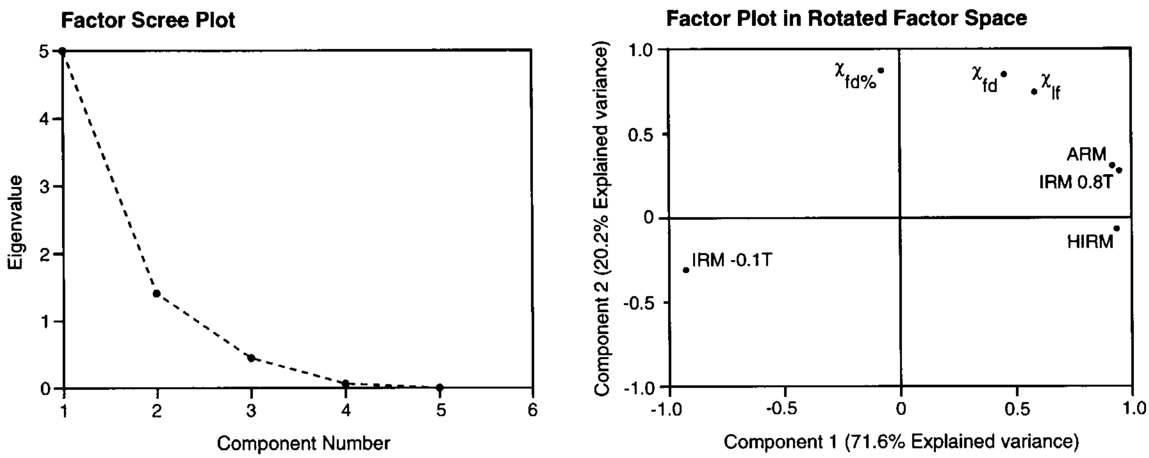

Figure 7. Eigenvalue plot (left) and Varimax rotated principal component solution (right) for mineral magnetic properties of the Old Mill catchment topsoils. Component 1 is the hematite (canted antiferromagnetic) component. Component 2 is the magnetite (ferrimagnetic) component

Table V. Varimax rotated principal component solution for Old Mill topsoils

	Component 1	Component 2
χ_{lf}	0·567	0·757
χ_{fd}	0·444	0·862
$\chi_{fd\%}$	–0·067	0·865
ARM	0·938	0·312
$IRM_{(0 \cdot 8T)}$	0·951	0·296
$IRM_{(-0 \cdot 1T)}$	–0·939	–0·325
HIRM	0·937	–0·053
Exp. var. (%)	71·6	20·2
Cum. exp. var. (%)	71·6	91·8

Figure 8b plots χ_{fd} and HIRM values for arable and woodland soil profiles in the Old Mill catchment. Both magnetic parameters vary little within the plough layer of the arable soil but change dramatically between 20 and 25 cm depth. Peak χ_{fd} values occur at 10 cm depth in the woodland soil and decline gradually below this depth. HIRM values are inversely related to χ_{fd} in both soil profiles.

Summary statistics describing the characteristics of seven subsoil samples are presented in Table III. These subsoils are characterized by a low χ_{lf}, χ_{fd}, $IRM_{(0 \cdot 8T, -0 \cdot 1T)}$ and S ratio, a high HIRM and a $\chi_{fd\%}$ of around 7 per cent, only some 2 per cent lower than topsoil values. There is little difference between measured ARM values in topsoils and subsoils.

Particle size controls on mineral magnetic signatures

The lake and reservoir sediments of Slapton Ley and the Old Mill reservoir have an upper particle size limit of around 63 μm (Foster and Walling, 1994; Foster *et al.*, 1996). Below 63 μm, the particle size distribution is multimodal and compares well with the particle size distribution of the sub-63 μm fraction of the catchment topsoils, with no apparent loss of fine sediments as a result of an expected decrease in trap efficiency for finer particles (Foster and Walling, 1994). In contrast, the sediments of the Start valley floodplain are often well sorted, with particle sizes ranging from >2 mm to <2 μm. The sub-63 μm fraction in this floodplain core ranges from over 97 per cent to less than 44 per cent of the total sediment mass.

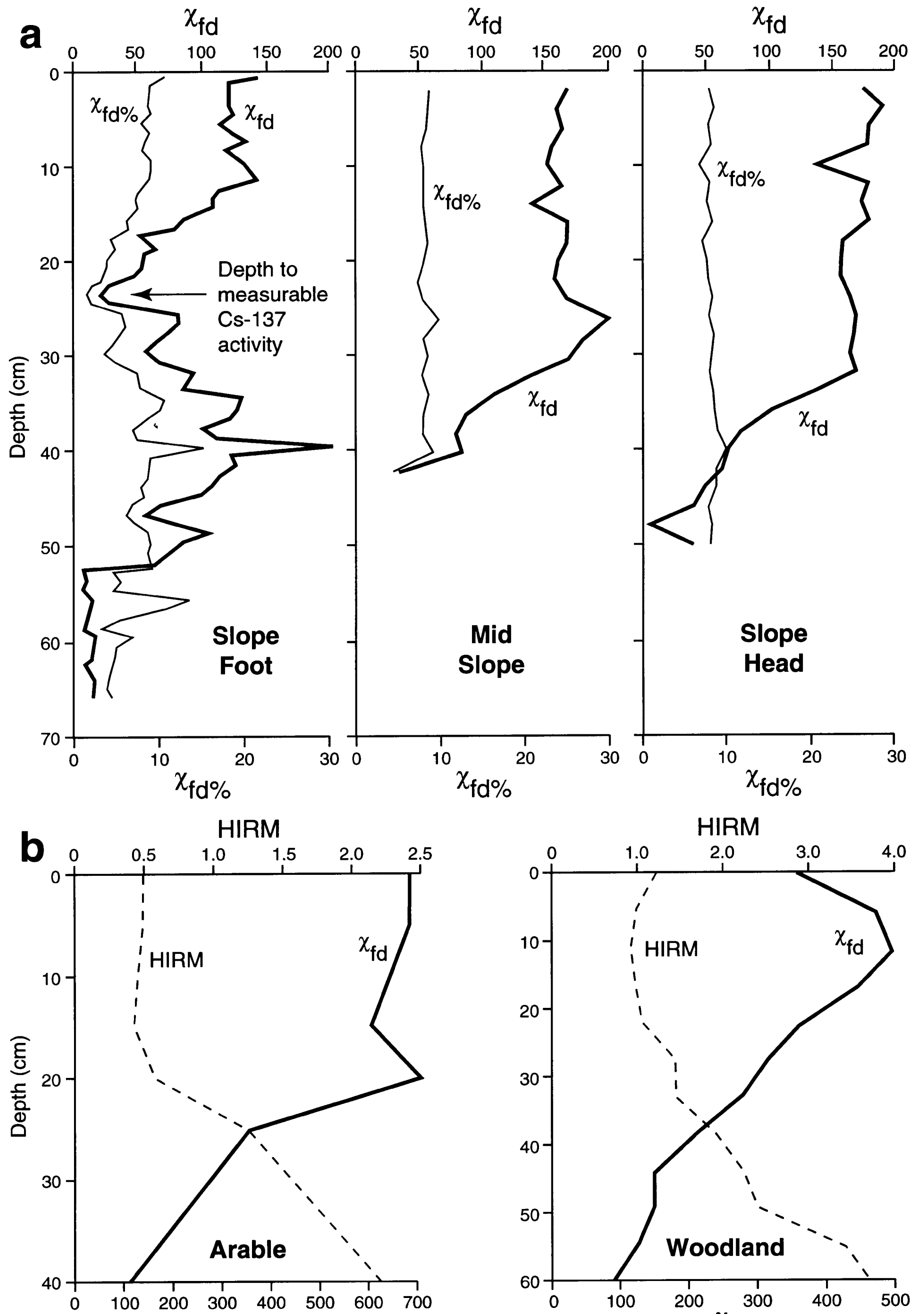

Figure 8. Downprofile mineral magnetic signatures in pasture soil cores collected from the Start catchment (a) and from arable and woodland soils in the catchment of the Old Mill reservoir (b)

Comparison between the treated and untreated subsamples during the fractionation of a bulk sediment sample from the Start valley (Figure 9) suggests that there are no significant changes to the magnetic signatures as a result of organic matter destruction and subsequent chemical dispersion. This suggests that the data of

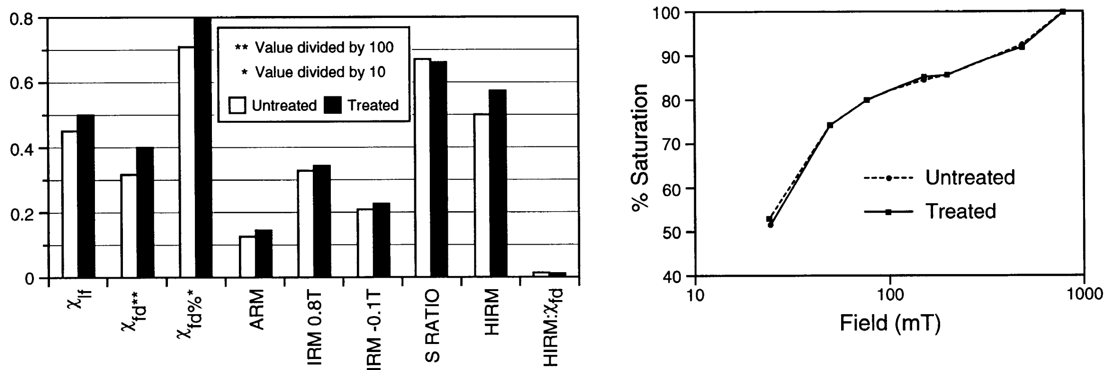

Figure 9. Effects of sample treatment and dispersion on magnetic properties and on the IRM acquisition curve

Table VI. Predicted and measured mineral magnetic characteristics of the fractionated floodplain sample (see text for explanation)

	χ_{lf}	χ_{fd}	$\chi_{fd\%}$	ARM	$IRM_{(0\cdot8T)}$	S ratio	$IRM_{(-0\cdot1T)}$	HIRM
Predicted	0·664	48·583	4·579	0·112	5·127	0·573	–3·370	0·879
Measured	0·597	39·800	6·700	0·187	4·767	0·644	–3·071	0·848

Figure 10 directly reflect particle size controls on susceptibility and remanence measurements. Many of the magnetic properties are enchanced in both the fine and coarse sediment fractions. This is particularly apparent for χ_{lf}, ARM, and the S ratio. χ_{fd} and $\chi_{fd\%}$ are enchanced in the finest particle size fraction, whilst $IRM_{(0\cdot8T)}$ and HIRM are enhanced in the coarse fraction. The HIRM:χ_{fd} ratio peaks in the 63–32 µm fraction and declines with increasing and decreasing particle size. Greatest depletion in this ratio occurs in the sub-2 µm fraction.

The proportion of the bulk sediment sample in each of the 11 particle size classes is also plotted in Figure 10. The sample is dominated by over 30 per cent in the <2 µm particle size range with some 51 per cent lying between the 63 µm and 2 µm particle size fractions. These data, coupled with the mineral magnetic signatures of each particle size fraction, were used to reconstruct the bulk mineral magnetic signature for comparison with that measured on the bulk sample (Table VI). Agreement between the measured and predicted values is quite good, although χ_{fd} is underestimated and $\chi_{fd\%}$ is overestimated relative to the measured sample.

Within the lake and reservoir sediments, particle size effects relate only to the sub-63 µm fraction whilst, for the floodplain cores, the whole range of the particle size distribution is valid. The range of values encountered in the data of Figure 10, however, would suggest that an interpretation of sources requires careful consideration where the particle size distribution of the sediment sinks varies significantly (cf. Björck *et al.*, 1982; Bradshaw and Thompson, 1985).

IMPLICATIONS FOR THE DEVELOPMENT OF MIXING MODELS

A number of significant implications arise from an analysis of the lake, reservoir, floodplain and soil mineral magnetic data presented above, for the development of reliable mixing models or catchment source interpretations based on the magnetic signatures of sediment accumulating in the Old Mill reservoir, Slapton Ley and the Start valley floodplain.

In developing such interpretations or models, it must be assumed that the major input components (in this case topsoil and subsoil) are characterized by good separation and low spatial variability. Furthermore, it must be assumed that the signatures remain stable at the site of deposition. Whilst the data in Table III suggest that the first assumption may be achieved with several magnetic characteristics, the second assumption appears to be valid only for the sediments of the Old Mill reservoir, since the summary statistics indicate that the means of the

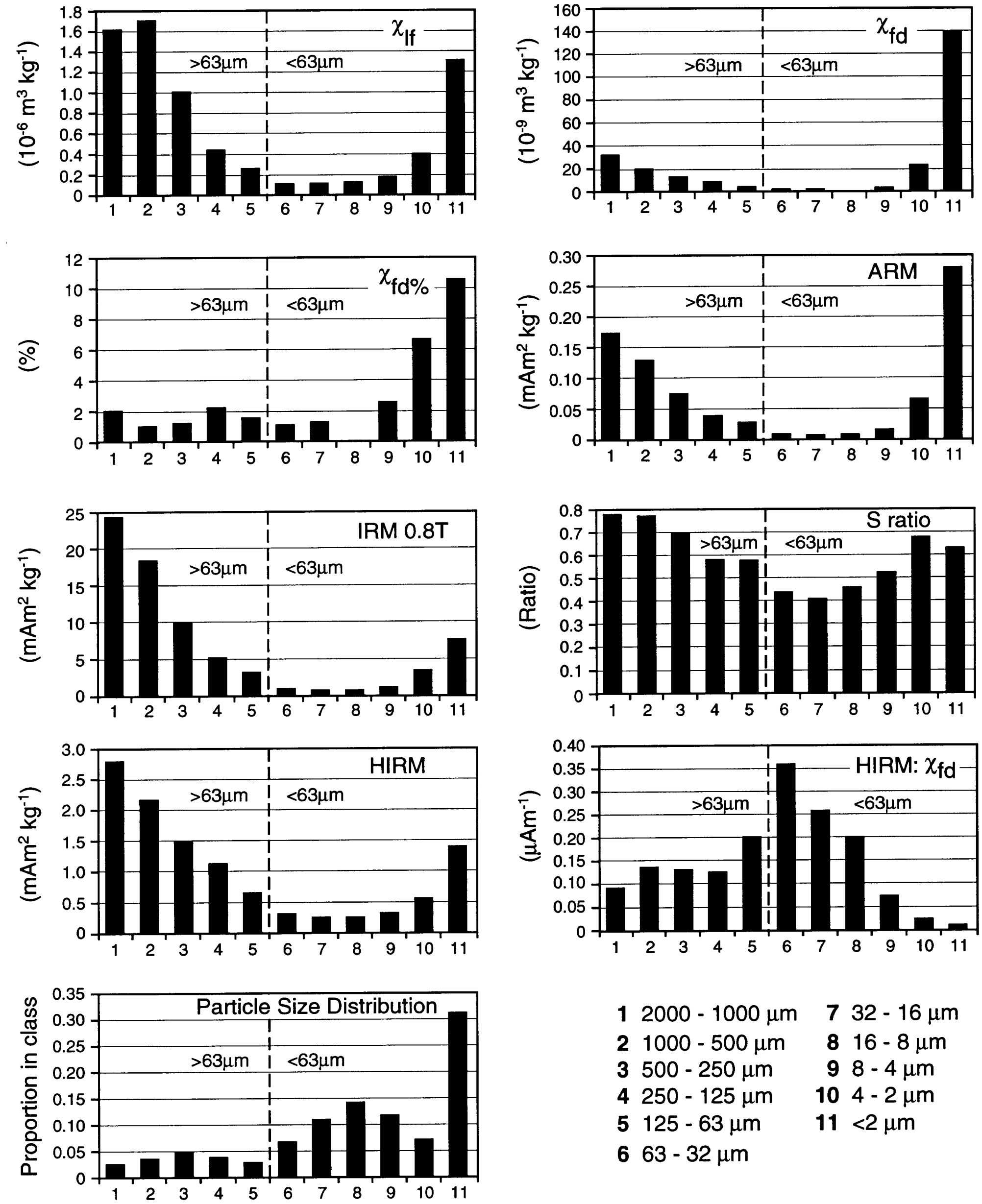

Figure 10. Particle size controls on the mineral magnetic signatures of a sediment sample collected from the Start valley

mineral magnetic data for the Slapton Ley and the floodplain sediments often lie outside the range of the topsoil and subsoil values. There are several possible explanations for these discrepancies.

Bulk signatures were measured for all three sediment cores. Whilst the soils were sieved to extract the sub-63 µm fractions in order to provide comparable particle size distributions to those of the lake and reservoir sediments, the floodplain sediments are characterized by a wider range of particle sizes, with some sections of the core dominated by coarse well-sorted high energy flood deposits. The sensitivity of the magnetic signatures to sorting, as demonstrated by the data presented in Figure 10, would suggest that χ_{lf}, $IRM_{(0{\cdot}8T)}$ and HIRM would be enhanced significantly in the coarser fractions. No attempt has been made to model the sediment source linkages for this floodplain core, since the coarser soil fractions have not been analysed. However, in order to develop a reliable predictive model for sediment sources using the floodplain mineral magnetic record,

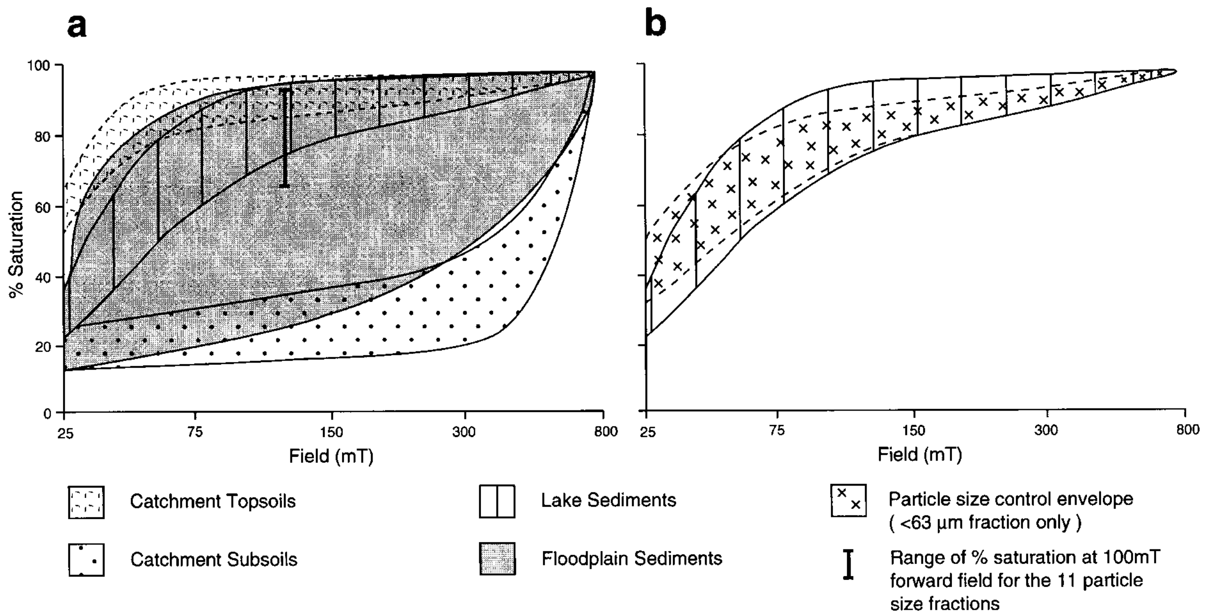

Figure 11. IRM acquisition envelope curves for topsoils, subsoils, lake sediments and Start valley floodplain sediments in the Slapton Ley catchments (a) and for particle size fractionated Start valley floodplain sediments (b)

it seems likely that narrow particle size fractions would have to be modelled on a separate basis in order to account for particle size controls.

The sediments of Slapton Ley have similar particle size distributions to the sub-63 μm fraction of catchment soils, yet many of the susceptibility and remanence signatures lie well below the range of the topsoil and subsoil data sets, despite correcting for a variable organic matter content and taking account of diatom silica concentrations. The susceptibility parameters appear to be more significantly depleted than the remanence parameters, which leads to a significant increase in the HIRM:χ_{fd} ratio throughout the core. χ_{lf} is roughly proportional to the concentration of ferrimagnetic minerals (especially magnetite) within the sample, whilst a high frequency dependency suggests the presence of viscous grains lying at the stable single domain/superparamagnetic boundary (Thompson and Oldfield, 1986). High frequency dependency is commonly associated with topsoils, but values often decrease in subsoils, especially those subject to waterlogging and gleying (Thompson and Oldfield, 1986; Dearing *et al.*, 1995). Decreases in χ_{lf}, χ_{fd} and $\chi_{fd\%}$ are recorded in the valley-bottom topsoils adjacent to the river channel as shown in Figure 6.

IRM acquisition curves for catchment topsoils and subsoils from the Start catchment are plotted in Figure 11a and show good magnetic separation of the potential sources. Topsoils are characterized by values approaching saturation at relatively low field strengths of around 50 mT. They have high S ratios, as indicated in Table III, and are characteristic of stable single-domain ferrimagnets. They are described here as magnetite-dominated sources. Subsoils require a high field of over 500 mT before samples approach saturation. They have lower S ratios than topsoils (Table III), but a much higher IRM$_{(0\cdot8T)}$:χ_{lf} ratio. This is characteristic of multidomain/stable single domain antiferromagnets such as hematite. They are described here as hematite-type sources.

The envelope plots describing IRM acquisition curves for lake sediment and floodplain cores from Slapton are also included on Figure 11a. The lake sediments exhibit magnetite-type responses similar to those of topsoils. By contrast, the floodplain sediments exhibit a range of IRM acquisition curves spanning almost the entire range of topsoils and subsoils. Whilst the lake sediment envelope appears to indicate a dominance of topsoil, the floodplain core is more difficult to interpret as a result of the dual effects of particle size and sorting. An indication of the possible particle size control on the IRM acquisition curve envelope for the floodplain sediments is given by plotting the range of percentage saturations for the 11 particle size fractions at a forward field of 100 mT (Figure 11a). With well sorted sediments, almost 50 per cent of the variation in percentage saturation at this field could be accounted for by particle size. The IRM acquisition curve envelope for the lake

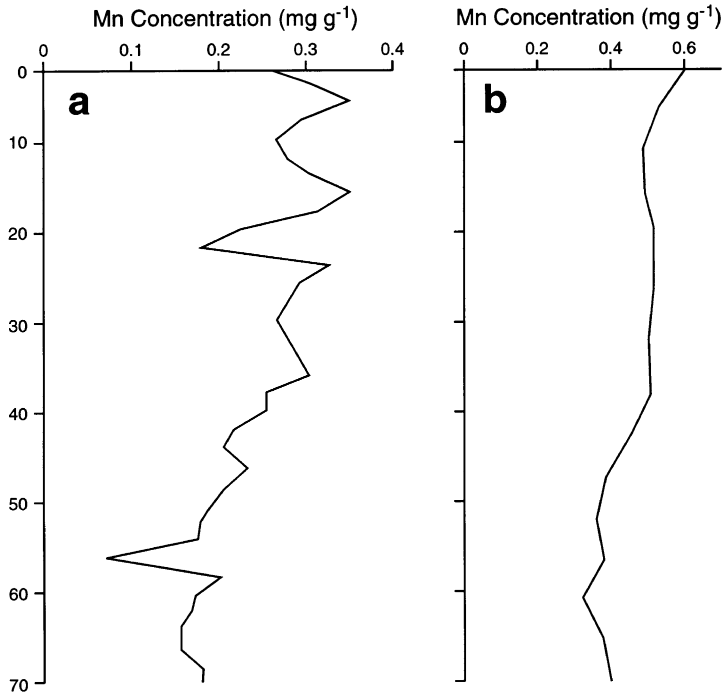

Figure 12. Mn concentrations in the sediments of Slapton Ley (a) and the Old Mill reservoir (b)

sediments is of a similar range to that described by envelope curves for the six particle size fractions of less than 63 μm diameter of the Start valley floodplain sediment sample shown on Figure 11b.

The declining, and significantly lower mean χ_{lf}, χ_{fd}, $\chi_{fd\%}$ and ARM values in the lake sediments of Slapton Ley in comparison to catchment sources, probably reflect the post-depositional dissolution of magnetite in the lake sediments. This process has been described for other small hyper-eutrophic lakes in the UK (Anderson and Rippey, 1988). χ_{lf}, χ_{fd}, $\chi_{fd\%}$ and ARM in the sediments of Slapton Ley are strongly correlated ($P<0{\cdot}05$) with the Mn concentration plotted in Figure 12, which suggests that changes in both the chemical and magnetic profiles reflect similar causes. Low values are associated with low Mn concentrations suggesting that dissolution is occurring under anoxic conditions. Whilst Slapton Ley is shallow, Bark (pers. comm.) has recorded zero dissolved oxygen concentrations and significant phosphorus release at the sediment–water interface during calm weather conditions in late summer, although these conditions are short-lived. Furthermore, O'Sullivan (1994) has suggested that 'mild eutrophication' of Slapton Ley commenced in *c.* 1910 and that the present highly eutrophic status has been reached since the post-Second World War intensification of agriculture. The upcore increase in χ_{lf}, χ_{fd} and ARM is therefore most likely to reflect the dissolution of magnetite at depth over the history of the sediment record rather than a change in catchment sediment sources as suggested by O'Sullivan (1994). HIRM shows similar upcore increases to χ_{lf} and χ_{fd} and the mean value lies slightly below the minimum values recorded in topsoils (Table III). HIRM and the HIRM:χ_{fd} ratio are also significantly correlated with Mn concentrations ($P>0{\cdot}05$). This would suggest that hematite-type, as well as magnetite-type minerals, are being lost from the lake sediments as a result of mineral dissolution.

The more rapid sediment accumulation in the Old Mill reservoir, coupled with relatively stable and significantly higher Mn concentrations than the Slapton Ley sediments (Figure 12b), suggests that post-depositional diagenesis of magnetite and/or hematite is of less significance at this site, although concentrations decline slightly, by *c.* 0·1 mg g^{-1}, below 45 cm depth. Furthermore, the range of mineral magnetic parameters for the Old Mill sediments lie well within the range of potential catchment sources. An attempt has therefore been made to develop a simple mixing model for the relative contribution of topsoil and subsoil sediment sources at this site.

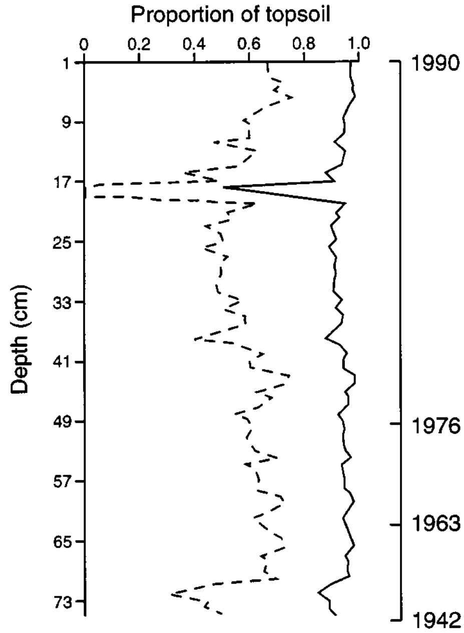

Figure 13. A mixing model identifying changing topsoil contributions to the sediments of the Old Mill reservoir based on average values of Table III (solid line) and for one standard deviation below the average topsoil and subsoil values (dashed line)

The PCA suggested that optimal mineral magnetic discrimination of sources could be achieved by using one susceptibility and one remanence parameter. Consequently, a simple two-component mixing model has been developed using the average HIRM:χ_{fd} ratios of all topsoils (0·006) and all subsoils (0·046) from Table III as a first approximation of the relative significance of the two sediment sources. Results of this modelling exercise are given in Figure 13. The average model results are plotted as a solid line and the 68 per cent confidence limit associated with the lower standard deviation for both topsoils and subsoils is plotted as a dashed line. The model has been constructed such that limits cannot exceed a 100 per cent contribution from either source.

One major change of source is identified at 18–19 cm depth in the core. This event has been described in detail by Foster and Walling (1994) and is marked in shallow water cores close to the main inflowing river by a coarse 2–3 cm thick sedimentary layer, although in this deep water core there is no evidence of a significant increase in the 90th percentile particle size at this depth in the sedimentary sequence. The model suggests that over 50 per cent of the sediment associated with this event is derived from subsoil (either derived from deeply eroded rills or channel bank) sources rather than topsoil. The remainder of the sequence is dominated by topsoil contributions, although the model suggests that channel bank sources became more significant (*c*. 10 per cent of the total) between *c*. 40 cm and 10 cm depth in the sedimentary sequence.

Whilst there is good discrimination between topsoil and subsoil sources using the HIRM:χ_{fd} ratio, and the sedimentary sequence appears to reflect catchment inputs rather than diagenesis or dissolution, the large error estimate remains problematic. Variability in the topsoil signal undoubtedly reflects topography and soil depth. Variations in the subsoil record have yet to be fully evaluated, but are an inherent component of environmental data.

CONCLUSIONS

A number of important general conclusions can be drawn from the analysis presented above.

- Whilst downcore trends in mineral magnetic signatures can often be detected in lake, reservoir and floodplain sediments, interpretation of the record may be problematic. In the well sorted floodplain sediments of the

Start valley, it is suggested that fractionation of the sediments into relatively narrow particle size bands will be required for the development of valid mixing models.

- The interpretation of the mineral magnetic signatures of sediments collected from the highly eutrophic Slapton Ley is problematic since the evidence suggests that the signatures are controlled by the dissolution of ferrimagnetic minerals (magnetite), and canted antiferromagnetic minerals (probably hematite), under anoxic conditions, although the exact mechanism has yet to be determined. Dilution by organic carbon and diatom silica are insufficient to explain the lower mean values for these lake sediments in comparison with catchment soils. Furthermore, there is no substantive evidence in the data presented above to suggest magnetite production as a result of diagenetic or bacterial controls, although O'Sullivan (1994) has independently confirmed the high productivity of Slapton Ley and the trend towards hyper-eutrophic conditions since the 1940s through an analysis of the diatom remains in the lake sediments. If the interpretation of the dissolution of magnetic minerals in the sediments of Slapton Ley is correct, this may have significant implications for interpreting the geochemical records retained within the sediments.
- Variability in the mineral magnetic signatures of catchment topsoils is high and their differentiation inadequate to discriminate land use controls for modelling purposes. In part this variability reflects topographic position and soil depth, particularly in shallow soils where cultivation may bring subsoil material to the surface. However, good topsoil–subsoil discrimination is afforded by the parameters χ_{fd} and HIRM. The validity of using multiple magnetic signatures in developing mixing models is questionable when the magnetic signatures of the sources can only be resolved in terms of two major components (hematite and magnetite type). Furthermore, variability in the average concentrations of the two sources (topsoils and subsoils) used for the development of a mixing model for the sediments of the Old Mill reservoir adds considerable uncertainty to the prediction. The conceptual basis of the mixing model may also become questionable as a result of the incorporation of subsoil into topsoil by cultivation. Variability is inherent in environmental systems, and more attention should be paid to the uncertainty in the estimates produced.

The research presented above confirms several of the doubts identified in the introduction for the appropriateness of a detrital model for interpreting the magnetic mineral origin of lake sediments in this case study, particularly those of Slapton Ley. It emphasizes the need for geomorphologists to pay more attention to the impact of particle size controls, diagenesis and dissolution before interpreting or attempting to model the mineral magnetic signatures in the sedimentary record.

ACKNOWLEDGEMENTS

We wish to acknowledge the contribution of Heather Dalgleish, Carolyn Holt, Rachael Rowe and Fiona Swan of Coventry University for assistance during numerous field sampling exercises and for allowing further analysis of data contained in unpublished undergraduate dissertations. The assistance of Qingping He with the collection of sediment cores is gratefully acknowledged and Libby Foster is thanked for help on the development of the mixing model. The logistical support provided by the Warden (Keith Chell) and staff of the Slapton Ley Field Centre during numerous field sampling exercises over the last 10 years is also gratefully acknowledged. The cartographers at Coventry University are thanked for producing high quality artwork from less than perfect originals. Two anonymous referees made valuable contributions to the development of ideas which are reported in this paper.

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